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# MELCOR Simulation of Containment Spray for Potential Regulation of 100TBq Cesium-137 Release from OPR1000

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## 1. Introduction

Safety regulations of nuclear power plant (NPP) over severe accident are more importantly considered after Fukushima accident. Restriction of radionuclide release to the environment is regarded as the most significant target for regulation. Some radionuclides such as Cs-137 and I-131 can be leaked into environment under unsuccessful severe accident management. International nuclear community has considered a new regulation for radioactive release of Cs-137 limited to 100TBq. Validation of this standard was performed by many researchers recently [1].

Since quantitative criterion was suggested, it is important to investigate whether current mitigation strategy complies with this regulation. The most effective measure to mitigate radionuclide release is considered as a containment spray system (CSS) in the present NPPs. The CSS directly sprays droplets, which entrains floating radionuclides in the containment. So investigation on effectiveness of the CSS method for mitigating leakage of radionuclide is needed in the suggested criterion of 100TBq of Cs-137.

Therefore, numerical analysis of mitigation effect by CSS in the hypothesized severe accidents was conducted in this study. As a first step for examining aspect of mitigation by the CSS, MELCOR 1.8.6 was used in this research. MELCOR is an advanced computational aid widely used for severe accident analyses. Also the Optimized Power Reactor 1000 MWe (OPR1000) was selected as reference NPP. Plant specifications of the OPR1000 were obtained from the Final Safety Analysis Report (FSAR).

## 2. Description of MELCOR simulation

### *2.1 MELCOR Input Model of OPR1000*

The MELCOR input model for the OPR1000 was utilized in this study. This model includes a core, a downcomer, a lower plenum, a upper plenum, a four cold legs, two hot legs, a pressurizer, two steam generators and four safety injection tanks (SITs), etc. Not only the primary and secondary systems but also the system attached to containment structure are modeled in this model [2]. Especially, the CSS is modeled to spray water droplets absorbing radionuclides including cesium in the containment.

To simulate release of cesium into the environment, the original input model was modified for accurate containment leakage. The leakage from containment can be divided in two ways; leakage by defects and rupture as showed in Fig 1. Leakage by defects indicates leakage only by defects in the containment especially in joints of the structure. On the other hand, leakage by rupture occurs when containment is disrupted by high pressure or external breach by collision. In case of leakage by defect, the FSAR restricts an amount of release into environment to 0.1 percent of inside containment by standard of air mass during 24 hours after LOCA. Also the containment can be ruptured partially when containment pressure reaches 0.9115 MPa or faces with high pressure continuously for a 36 hours [3].

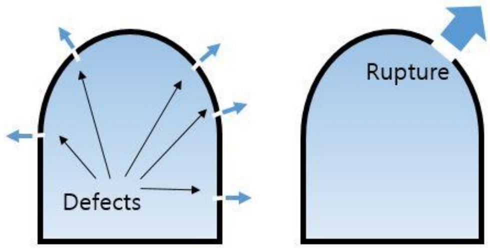


Fig.1 Diagram of leakage by defect (left) and leakage by rupture (right) in containment

Therefore, the MELCOR input was modeled to embrace all these criteria. Leakage by defect was simulated by flow path around containment penetration because region of containment penetration was evaluated to the most vulnerable region in terms of leakage. Sum of flow paths area was determined as 10.17 $cm^2$ in consequence of repetitive simulation to match 0.1 percent criteria. Table 1 shows an amount of air leaked and corresponding percent to mass in containment during 24 hours after LOCA. Transient behavior can be found in Fig. 2. On the other hand, a partial rupture bringing another leakage was assumed to occur at 0.4412 MPa, which is a leak pressure designed in the current containment.

Table1. An amount of air leaked into environment from containment during 24 hours.

| | Mass (kg) | Percent (%) |
|---|---|---|
| $N_2$ | 76.44 | 0.108 |
| $O_2$ | 21.56 | 0.103 |

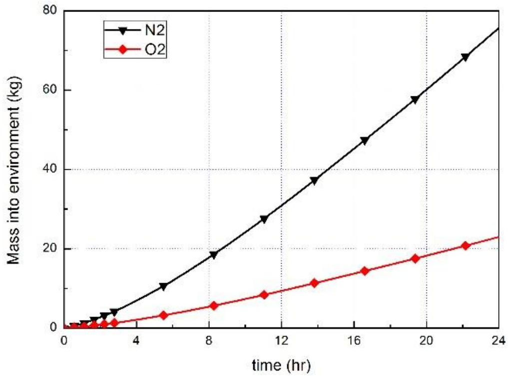


Fig. 2 Released air into environment from containment by leakage of defects following time

*2.2 Containment Spray System (CSS) Model*

In the MELOR simulation, the droplets heated up and cooled down by the CSS are circulated by forced convection. So forced convective heat transfer coefficient is used to compute heat and mass transfer rates. These are integrated by a Runge-Kutta method over the fall height of the spray droplet to obtain the final droplet mass and temperature. Total heat and mass transfer rates are calculated by multiplying the rates for one droplet by the total number of droplets or the same size and summing over all droplet sizes. Size of droplet is determined by its temperature and height on each occasion as shown in Equations (1)-(3). Also it is assumed that droplets are spherical and isothermal.

$$\frac{dm}{dt} = -2\pi\rho_g D\left(1 + 0.25Re^{\frac{1}{2}}Sc^{\frac{1}{3}}\right)D_e \ln(1+B) \quad (1)$$

$$\frac{dT}{dt} = \frac{1}{mc_{pl}}\left[\frac{c_{pv}(T-T_{cv})}{(1+B)^{\frac{1}{Le}}-1} + h_{fg}\right]\frac{dm}{dt} \quad (2)$$

$$\frac{dz}{dt} = \left[\frac{4(\rho_d-\rho_g)gD}{3\rho_g C_d}\right]^{\frac{1}{2}} \quad (3)$$

Details of the CSS are shown in Table 2. Spray was installed in containment dome, so it was located at 57.0 m. Initial temperature and diameter of droplets were set to value of room temperature. Also total volume of Refueling Water Tank (RWT) was utilized for spray only and its volume was 2271 $m^3$ and total volumetric flow rate of spray was 0.45 $m^3$/sec specified in the FSAR.

Table 2. Details of CSS

| Parameter | Value |
|---|---|
| Elevation (m) | 57.0 |
| Spray source | RWT |
| Capacity ($m^3$) | 2271 |
| Initial temperature of droplets (K) | 300 |
| Initial diameter of droplets (m) | 1.0e-3 |
| Total volumetric flow rate ($m^3$/sec) | 0.45 |

*2.3 Accident Scenario*

Initial accident was selected as SBLOCA without SI, SBO, and TLOFW, which show the highest possibility to transition into the severe accident. Table 3 shows that possibility for each initial accident [4]. In case of SBLOCA, cold leg break of equivalent diameter of 1.36" was assumed. Safety Injection (SI) was assumed unavailable. Also failure of all systems including reactor coolant pump (RCP) which used electricity was assumed in SBO accident. TLOFW accident was assumed to occur by losing all main and auxiliary feed water. For these three accidents, CSS mitigation effect was assessed using MELCOR 1.8.6 code. Major accident sequences for each accident are summarized in in Table 4.

Table 3. Possibility to SA by each initial accident

| Initial accident | Possibility to SA |
|---|---|
| SBLOCA without SI | 22.4 % |
| SBO | 14.4 % |
| TLOFW | 13.8 % |

Table 4. Sequence of each accident

| Events (hr) | SBLOCA without SI | SBO | TLOFW |
|---|---|---|---|
| Accident start | 0 | 0 | 0 |
| Reactor trip | 0.04 | 0 | 0.01 |
| RCP trip | 0.06 | 0 | 0.37 |
| SG dryout | 1.74 | 1.04 | 0.27 |
| Oxidation | 2.35 | 2.29 | 1.08 |
| Cladding melt | 2.64 | 2.65 | 1.36 |
| $UO_2$ melt | 2.67 | 2.67 | 1.38 |
| Relocation to lower plenum | 2.89 | 2.83 | 1.56 |
| SIT injection | 3.64 | 3.80 | 2.33 |
| SIT exhaust | 5.89 | 3.94 | 2.45 |
| RPV failure | 5.82 | 3.78 | 2.30 |

The main objective of this study is to investigate the CSS effect on the mitigation of the Cs-137 release. Thus all other safety systems excluding CSS and Safety Injection System (SIT) were assumed inoperable. For clear comparison, an amount of cesium leaked during each accident was calculated in two cases with and without the CSS. Since the spray potentially exhibits adverse effects of increasing hydrogen fraction and wetting equipment in containment, spraying at the earliest time may not be a best choice [5]. Thus, repetitive simulation was proceeded to find the most reasonable time to initiate spray in this OPR1000 model.

## 3. Results and Discussion

### *3.1 Release of cesium without CSS*

As mentioned in Section 2.1, containment leakage is classified according to route, leakage of defects and rupture. Because partial rupture occurs when containment pressure reaches 0.4412 MPa, gaseous materials can be released only by defects before 24 hours after each accident. Fig 3 shows mass of cesium into environment during the first 24 hours. SBLOCA caused 5 gram more leakage compared to the SBO and TLOFW. Considering an amount of cesium being relevant to 100 TBq is about 31g, 5 grams of cesium could make a significant impact on the severe accident management. Therefore, if leakage occurs only by defects not by a rupture, safety standard about radionuclide is satisfied even without the CSS.

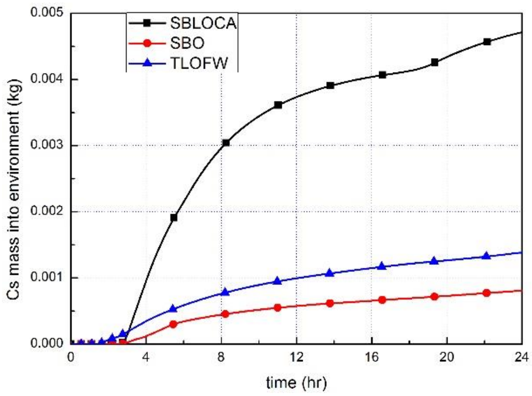


Fig. 3 Cs mass into environment from containment during 24 hours after each accident

However, if containment undergoes the partial rupture, different situation may be postulated. Each accident showed different timing of partial rupture and reaching 100 TBq as shown in Table 5. Since gases including cesium are directly ejected from the break, partial rupture and reaching 100 TBq happened earlier in the SBLOCA. Fig. 4 showed cesium mass during 60 hours, which includes the period after the partial rupture. Until leakage by rupture started, over 24 hours every accident released a little amount as expected. But after partial rupture, it was emitted explosively. Leakage in the SBLOCA was overwhelmingly larger than the other accidents, in which cesium release was much more than 31 g. Consequently, it is expected that the CSS is inevitably needed to mitigate release of radionuclide in severe accident especially by leakage of rupture.

Table 4. Specific time of each accident

| Initial accident | Partial rupture | 100 TBq |
|---|---|---|
| SBLOCA | 30.84 | 30.97 |
| SBO | 37.34 | 41.25 |
| TLOFW | 35.90 | 39.13 |

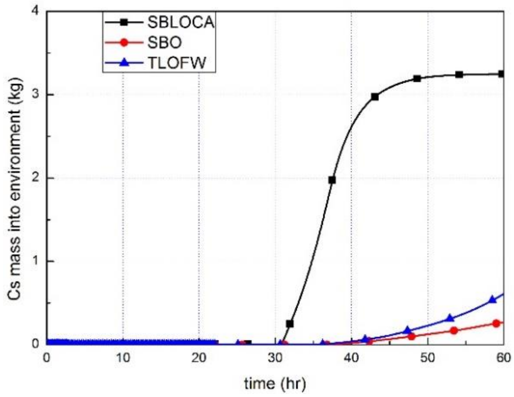


Fig. 4 Cs mass into environment from containment during 60 hours after each accident

### *3.2 Release of cesium with operating CSS at 100 TBq*

Objective of operating CSS is mitigation of cesium release into environment under 31g in this study. At first, the CSS was set to start operation at time of reaching 31 g release to the environment. As the spray started to drop droplets, radionuclide of aerosol including cesium started to be absorbed. Fig. 5 showed variation of its mass into the environment. Red dotted horizontal line indicated the limit of 31 g and starting point of the spray. It is shown that CSS was effective to limit an amount of released cesium at fixed quantity but it exceeded 31 g. To satisfy the 100 TBq limit, it should be considered that the spray operation needs to perform before partial rupture occurs.

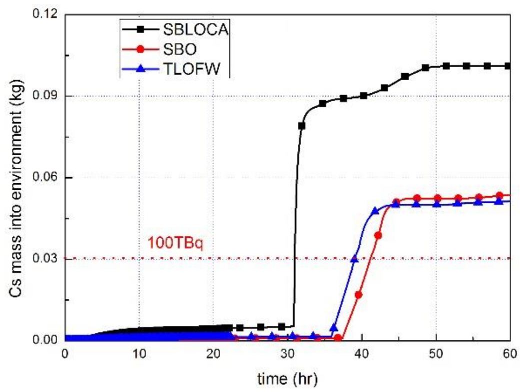


Fig. 5 Cs mass into environment from containment during 60 hours after each accident with CSS

### *3.3 Release of cesium with operating CSS at lower than 100 TBq*

To satisfy the 100 TBq limit, three cases of simulation, starting spray at 5 g, 10 g, and 15 g of cesium release into environment were conducted. SBLOCA was selected as the representative case because SBLOCA showed more severe consequence than the other accidents. Fig. 6 shows results of the three cases in SBLOCA. The earlier starting of spraying induced the lesser amount of cesium release. However, Cs mass difference between spray operation at 5 and 10 g release was entirely different to difference between spray operation at 10 and 15 g. This is because partial rupture occurred in between the time of reaching 5 g and 10 g. This implies that if containment is partially ruptured before starting spray, it is difficult to mitigate release no matter how spray started operation early. On the other hand, because leakage of defects is much less than the limit, the CSS has only to starting before partial rupture to satisfy the limit. As a result, the most important parameter for finding spraying time could be pressure of containment causing partial rupture.

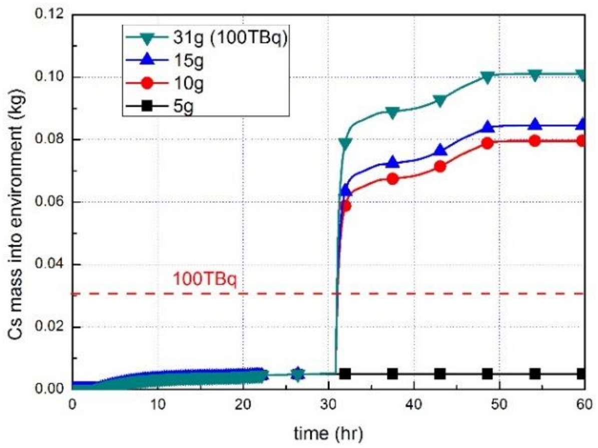


Fig 6. Cs mass during 60 hours after SBLOCA with different starting time of spraying

## 4. Conclusions

In this research, mitigation strategy of the CSS in severe accident of OPR1000 was studied to comply with safety limit of 100 TBq cesium using MELCOR. Spray was shown to exhibit excellent performance to restrict release of radionuclide. However it also generates adverse effects of steam condensation and subsequent increase of hydrogen concentration. Therefore, finding a reasonable spraying time during severe accident is essential to accident management of the NPP. Major findings and future work in this study could be summarized as follows.

(1) Leakage model considering both leakage of defects and rupture was developed in the MELCOR input.
(2) Even though all safety systems excluding SIT were inoperative, exceeding the cesium release limit by leakage of defects was not foreseen. On the other hand, a partial rupture caused dramatic leakage well over the limit in a short time. Therefore, spray must be operated before containment partial rupture.
(3) If containment was partially ruptured by high pressure before spraying, it will be challenging to satisfy the limit by the actuation of the CSS. Thus the most important parameter for finding spraying time was identified as containment pressure at the time of partial rupture.
(4) The severe accident simulation in this study was conducted with assumption that all safety system excluding SIT and CSS was disabled state. Therefore, for more practical analysis, additional simulation is needed with other operable safety systems.

## Acknowledgements

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## REFERENCES

[1] Silva, K., & Okamoto, K. (2015). Applicability of 100 TBq cesium 137 release into environment as a safety criterion for consequence assessment at reactor design approval stage. Journal of Nuclear Science and Technology, 52(12), 1530-1539.
[2] Lee, Y., Choi, W., Seo, S., Kim, H. Y., & Kim, S. J. (2016). Development of safety injection flow map associated with target depressurization for effective severe accident management of OPR1000. Journal of Nuclear Science and Technology, 1-11.
[3] KHNP, Shin Kori 1&2 final safety report, Korea Hydro and Nuclear Power, 2008
[4] Kim, J., Lee, U., Hong, S. W., Kim, S. B., & Kim, H. D. (2006). Spray effect on the behavior of hydrogen during severe accidents by a loss-of-coolant in the APR1400 containment. International communications in heat and mass transfer, 33(10), 1207-1216.
[5] Hanyang University, Analysis of postulated regulatory requirement for severe accident management strategies of OPR1000 using MELCOR code, 2015